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Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England

Tianqi Li*, Anthony Paul Roskilly, Yaodong Wang

Sir Joseph Swan Centre for Energy Research, Newcastle University, United Kingdom

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ABSTRACT

This paper proposes a comprehensive sustainability assessment model incorporating (a) life cycle approach and sustainability theory. In the model, sustainability is assessed from three categories: techno-economic, environmental and social. A total of thirteen indicators were included in the proposed model, with five evaluating the techno-economic performance, six evaluating the environmental performance, and two examining the social impact. The effectiveness of this model is then demonstrated through its application to a case study of solar photovoltaic in the North East region of England. Three types of the most commonly deployed solar photovoltaic electricity generation systems are included in the case study: monocrystalline (s-Si), polycrystalline (p-Si) and Cadmium telluride (CdTe) thin film.

The multi-silicon solar photovoltaic system is found to be the most sustainable option for its high performance in the techno-economic and environmental categories; the CdTe based system is the least-favoured option across all three categories; and the polycrystalline system has the best performance across all categories. Energy conversion efficiency appears to be one of the most influential factors for the solar photovoltaic system's sustainability performance. Despite being the least costly system among the three, the CdTe system appears to be the least financially viable option mainly due to its low energy-conversion efficiency.

This study estimates the environmental impact of selected technologies using the CML2001 method and then employs ReCiPe method to cross-validate the estimated results. Identical results were found for all indicators apart from eutrophication potential, due to the difference in impact quantification methods between CML and ReCiPe.

1. Introduction

The increasing demand-supply ratio of global oil reserves and climate change are driving the adoption of renewable energy as a desirable alternative to fossil fuels. However, due to uncertainties surrounding the energy technologies concerned and the complexity of the power system, a comprehensive assessment of all energy options is essential for exploring the sustainability performance of energy technologies and identifying their sustainability burdens [1], and thus assist decision-making and provide a solution to improve the sustainability of energy technologies [2–4].

The "three pillars" of sustainability, also known as "triple bottom line" refers to the three core components of societal development: environment, economy, and social values [5]. These values need to be equally represented in order to achieve sustainable growth [6–8]. However, observing from current practice, although terms such as "Integrated Assessment" and "Triple-bottom-line Assessment" are widely used in literature, there is little consensus regarding the use of the term Sustainability Assessment [9]. There is a vast amount of literature covering sustainability assessment of energy systems that only focuses on one or two of the three pillars of sustainability (e.g. [10,11]); or employing only a qualitative research technique, (e.g. [12]) which not only lacks in depth of scientific enquiry, but also leaves room for uncertainties and bias.

A life cycle approach (also known as life cycle thinking) encourages taking account of a product's impact at every stage of its life cycle. The integration of the life cycle approach and the triple bottom line method forms the life cycle sustainability assessment (LCSA); this method not only ensures that all aspects of sustainability are tuned and checked against each other, but also guarantees consideration of the impact of a given product throughout its lifespan. In the words of Kloepffer [13],

* Corresponding author.
Email address: tli@live.co.uk (T. Li)

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the merit of a life cycle sustainability assessment method is "on feasibility and robustness even more than scientific brilliance and completeness."

Life cycle assessment (LCA) is the only internationally-standardised environmental impact assessment method, and it is underpinned by the life cycle approach [13]. It offers a complete review of sustainability impact throughout a product's entire life cycle, from "cradle-to-grave". LCA had soon become favoured by academics and industries since it was first developed in the 1960s, for its effectiveness in assisting in optimising environmental performance of a single product and its ability to enable a fair comparison between multiple products [14,15]. Over the past decade, LCA has become not only a powerful tool for scientific inquiries, but also the primary method for translating sustainability science into useful knowledge to support business and regulatory decision making.

The assessment method proposed by Youds [1] and Stamford and Azapagic [15] employs the life cycle sustainability assessment method and also uses the LCA method to account for energy technologies' environmental impact; it is by far the most comprehensive method for assessing the sustainability of energy technologies in the UK. Despite its comprehensiveness, however, the focus of this method remains at a national level, where regional characteristics are not taken into account. The significant impact of the geographical scale at which assessment is conducted is demonstrated through a number of studies in the 1990s [16]. As illustrated in Fig. 1, increased geographical scale of assessment may compromise the level of detail; on the other hand, downscaled assessment narrows the assessment scope [17]. Regional level is where social institution, ecological boundaries and economic phenomena overlap [18–20]; an assessment conducted on a regional scale is not only robust, it can also facilitate effective decision-making based on options that both use available natural resources and serve community priorities the best.

This study introduces a holistic and systematic regional life cycle sustainability assessment model which can be used to evaluate sustainability performance of electricity generation technologies. The practicality of this model is then demonstrated by applying to a case study of solar photovoltaic (PV) technology deployment in the North East region of England. To the author's knowledge, this is the first model of its kind. This paper also presents a novel indicator of circularity of energy technologies, and this indicator will be further explained in the following sections.

2. Method

In the model, electricity generated is regarded as a product, and sustainability performance of this product is examined throughout its entire life cycle using a group of indicators.

The design process of the model is displayed in Fig. 2. A survey of sustainability theory is first carried out to establish the theoretical framework of the assessment model; where the "triple-bottom-line" and life cycle approach are found to be the most suitable. In the second stage, the indicator selection, there are two distinctive main approaches to select indicators: the first one is the top-down approach, which means experts select and design the indicators; the other is the bottom-up approach, which features the participation of stakeholders in the framework design and indicator selection process [3]. In this model, both approaches are employed to ensure the robustness of assessing relevant sustainability issues. Over thirty sustainability assessment research articles and reports were reviewed in the literature survey, and stakeholders ranging from the energy industry to local city councils were consulted.

Selected indicators are divided into three impact categories in accordance to the three pillars of sustainability: techno-economic category, environmental category, and social category. The proposed model comprises of thirteen indicators in total, with five addressing the techno-economic impact, six addressing the environmental impact and two evaluating social impact.

The selected indicators must provide information about the main characteristics of the product from a sustainability standpoint [22]. The international guideline on life cycle assessment studies ISO14040 is adopted as the basis of indicator selection criteria for indicator quality assurance purposes, as follows:

1. Relevance to energy technologies
2. Avoidance of double counting
3. Indicators must be quantifiable
4. Feasibility of application

It shall be noted that the weighting method which includes applying the value of importance onto results of indicators [23] is not recommended as stated in ISO14040. Therefore weighting is not considered in this model.

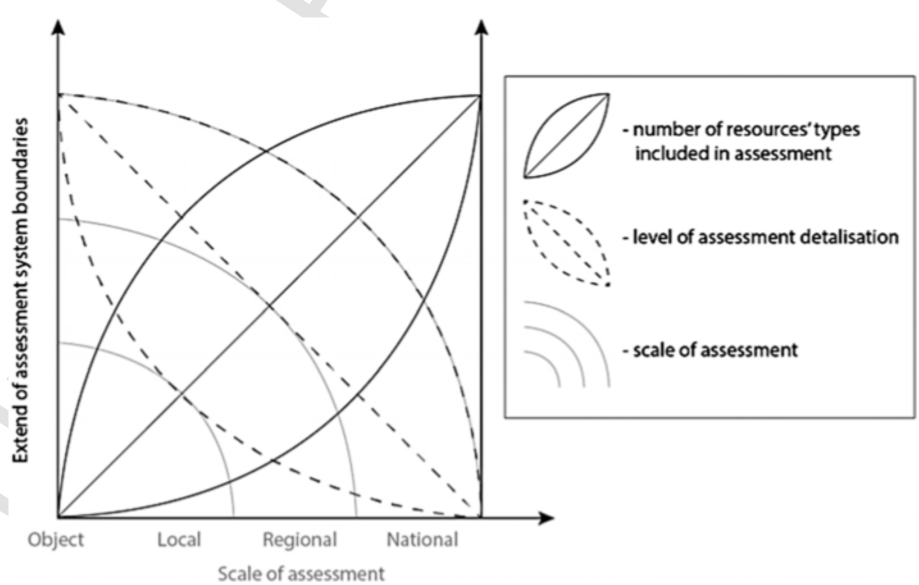


Fig. 1. Impact of sustainability assessment scale [21].

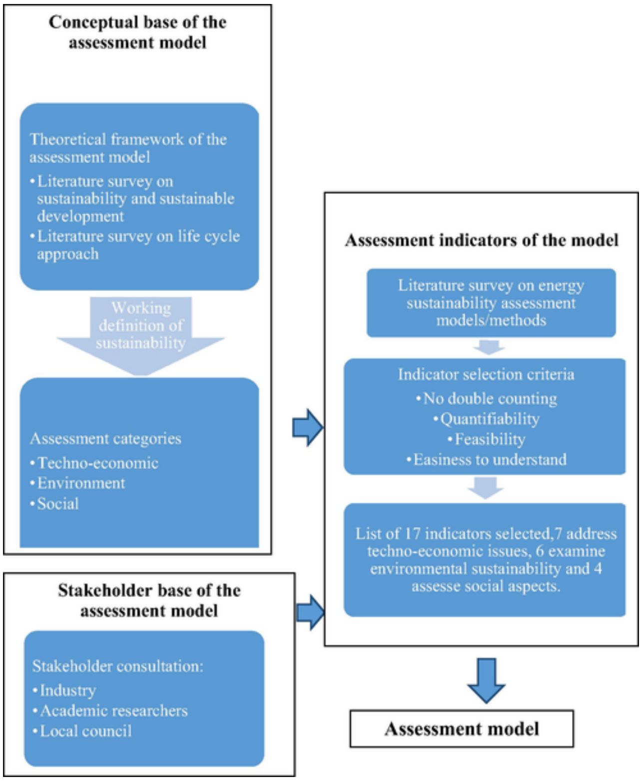


Fig. 2. Design process of the proposed sustainability assessment framework.

The completed assessment model is displayed in Table 1, and the indicators are further explained in following sections.

2.1. Techno-economic indicators

The techno-economic performance of an energy technology is examined in three categories: reliability, levelised cost of generation and profitability.

2.1.1. Reliability

Reliability of the technology is measured through two indicators: availability factor and capacity factor. Availability factor is the ratio of time in which a plant is available to generate electricity over its maximum working hours [24], and is calculated as (1):

$$Availability\ Factor = \frac{T_{work}}{T_{\max}} \times 100\ (\%) \tag{1}$$

where

T_{work}
$-Total\ hours\ the\ energy\ system\ is\ available\ to\ deliver\ power$
$T_{\max}$
$-Maximum\ annual\ working\ hours\ of\ the\ energy\ system$

Capacity factor is the ratio of a plant's actual output compared to its potential maximum output at full production capacity. This ratio varies in time and also depends on the availability of resources particularly in cases of intermittent technology such as solar and wind. It is calculated as (2):

$$Capacity\ Factor = \frac{E_{work}}{E_{\max}} \times 100\ (\%) \tag{2}$$

where

$P_{work} - Plant\ working\ capacity$
$P_{\max} - Plant\ maximum\ capacity$

2.1.2. Cost

Levelised cost of generation stands for the price to be paid for the energy technology to break even. It is included in capital cost as well as operational expense totals. Capital costs cover expenses at both the construction stage and decommissioning stage of an energy project, whereas operational costs cover costs generated for operation and maintenance of an energy project and expenditures on waste disposal. The total levelised costs are the sum of capital costs and operational costs. The formula for this indicator is an integration of methods by

Table 1
Sustainability assessment model with indicators.

	Sustainability issues	Indicator	Unit	Life cycle stage account for			
				Manufacture	Installation	Operation	End of life
Techno-economic Category	Reliability	Availability factor	%			x	
		Capacity factor	%			x	
	Cost	Levelised cost	£/MWh	x	X	x	x
	Financial feasibility	Payback period	years	x	X	x	x
		Profitability	Dimensionless	x	X	x	x
Environmental Category	Material circularity	Circularity	Dimensionless	x	X	x	x
	Energy payback	Energy payback period	Years	x	X	x	x
	Global warming	Global warming potential	$kgCO_2\ eq./MWh$	x	X	x	x
	Acidification	Acidification potential	$kgSO_2\ eq./kWh$	x	X	x	x
	Eutrophication	Eutrophication potential	$kgPO^{2}_{-4}\ eq./MWh$	x	X	x	x
	Ozone depletion	Ozone layer depletion potential	$kgCFC_{-11}\ eq./MWh$	x	X	x	x
Social Category	Fuel poverty	Bill reduction rate	%		X	x	x
	Employment provision	Employment provision	person-year		x	x	x

[25,26], as (3):

$$Levelised\ Cost = \frac{\sum_{n=1}^{N} \frac{CC+M_t+F_t}{(1+r)}}{E_t} \tag{3}$$

where

CC_t – Capital cost
M_t – Maintenance cost
F_t – Fuel cost
r – Discount rate
E_t – Energy harvested

2.1.3. Financial feasibility

The profitability of an energy technology is measured through its payback period and profitability. The payback period examines the amount of time for income generated through a technology to break even with total capital and maintenance expenditure as well as expenses on fuels. The payback period is calculated as (4):

$$Payback\ Period = \frac{CC + M_t + F_t}{FS_t + In_t} \tag{4}$$

where

FS_t – Financial support recieved
In_t – Income generated

The profitability index is an investment term to describe the efficiency of invested capital (Gifford et al., 2011) of technology from its economic performance through a cost-benefit ratio. The profitability index describes the net present value (NPV) of an investment option at any named time in the future. The higher value of a profitability index indicates a higher NPV, which indicates a stronger financial performance demonstrated by a technology [27]; on the other hand, if the value is less than one then the investment option is unlikely to be profitable at the selected future time. The profitability indicator is calculated as (5):

$$Profitability\ Indicator = \frac{\frac{FC_t}{(1+r)^t}}{CC} \tag{5}$$

where

FC_t – Future cash in flow in year t
r – Discount rate

2.2. Environmental indicators

One of the many strengths of LCA is its ability to produce results that are based on scientific data. There are two ways to calculate and visualise these results: mid-point, and end-point methods. These two approaches examine different stages in the cause-effect chain to calculate the environmental impact. The end-point method examines the impact at the end of the cause-effect chain such as the impact on human health and ecosystem quality, while the mid-point method examines the impact at the earlier end of the cause-effect chain, and specifically before the end is reached. Although the end-point method is favoured by decision makers for its simplicity in communicating LCA information, it suffers from a high level of uncertainty and thus the mid-point method is chosen for this study.

CML method [28] is applied in this study to calculate the environmental impacts, for it is the most well-established mid-point methodology and it is regional valid for European based cases [29]. Therefore the indicators (except circularity and energy payback indicator) included in this category are named in accordance with the CML methodology.

2.2.1. Material circularity

This paper introduces a novel indicator for measuring circularity of material use in energy technologies. The idea of material circularity originates from the concept of "circular economy". In contrast to the current economic paradigm of a "linear economy" where the production chain depends on the extraction of virgin material resources, a circular economy calls for an economy that sustains on the finite resources available by treating waste as resource and opportunity instead of a burden. The idea of the circular economy was first introduced in the 1960s [30], and further developed in the fields of industrial ecology [31], the blue economy [32] and cradle-to-cradle [33]. In 2015, the European Commission released its first Circular Economy Strategy and included the circular economy as part of its sustainable development policy [34], and in 2016 by the European Commission Environment Program and the Ellen MacArthur Foundation introduced a first official methodology for measuring material circularity [35]. As the first European-level official response to material circularity, this method has received mixed reviews. Criticism mainly surrounds its complexity of application, and also for its "Euro-centricicity" data requirement for carrying out the assessment [36].

The circularity indicator proposed in this paper is presented as (6):

$$Circularity = \frac{Material\ Circularity + Fuel\ circularity}{2} \times 100\ (\%) \tag{6}$$

Where material circularity is calculated as in (7):

$$Material\ Circularity = \frac{\sum_j^J (MR_{in} + MR_{waste})}{2 * M_{total}} \times 100\ (\%) \tag{7}$$

where

MR_{in} –Total of recovered material for energy system in life cycle j
MR_{waste} –Amount of recoverable waste generated in life cycle j
M_{total} –Total amount of material required for energy system

Moreover, fuel circularity is calculated as follows:

$$Fuel\ Circularity = \sum_j^J \frac{RF}{F_{total}} \times 100\ (\%) \tag{8}$$

where

RF – Amount of input fuel as recoverable material
F_{total} – Total fuel required for power generation

Down-cycled material can be included in the reusable material category if it can be used as feedstock. For example, a particular aluminium and plastic material mix can in theory can be re-used, but in reality that there is currently no market mechanism that supports such a process, and material as such cannot be considered as re-usable material.

2.2.2. Energy payback

The energy payback period is one of the most commonly-used indicators for evaluating whether the energy output of a particular technology breaks even with the energy consumption required for its manufacture, operation and end-of-life treatment. It is calculated as (9):

$$\textit{Energy Payback Period} = \frac{E_{in}}{E_{out}} \tag{9}$$

where

E_{in} – *Energy consumption for the energy system*
E_{out} – *Annual energy output from the energy system*

2.2.3. Global warming

Global warming potential is the total greenhouse gas emitted throughout the entire life cycle of the energy technology. The calculation follows the CML2001 impact method, as this is the most widely-used method of accounting for the life cycle climate change contribution of a product [37,38]. It is calculated as (10):

$$\textit{Global Warming Potential} = \sum_{x}^{X} GWP_x \times M_{gx} \tag{10}$$

where

GWP_x
–*Global warming potential (in* $kgCO_2eq.$*) of green house gas x*
M_{gx}
–*Total mass of green house gas emission per unit electricity generated*

2.2.4. Acidification potential

All activities involved in the life cycle of electricity production emit acidic gases such as sulphur dioxide, nitrogen oxides, ammonia and hydrogen chlorides, which all contribute to the acidification of water bodies and thus increase the mortality rate of aquatic organisms. The acidification potential of each acidic chemical is interpreted as a per kg of sulphur dioxide equivalent. The acidification potential of the energy technology is calculated as (11):

$$\textit{Acidification Potential} = \sum_{x}^{X} AP_x \times M_{ax} \ (\mathrm{kgSO_2\ eq./kWh}) \tag{11}$$

where

AP_x
–*Acidification potential (per* $kgSO_2$ *eq.) of emission x*
M_{ax}
–*Total mass of acidic emission x per unit electricity generated*

2.2.5. Eutrophication potential

Eutrophication potential measures the excessive richness of nutrient in waterbodies introduced by the assessed energy technology, which promotes excessive growth of biomass in the ecosystem. It is calculated as:

$$\textit{Eutrophication Potential} = \sum_{x}^{X} EP_x \times M_{ex} \ (\mathrm{kgPO_{-4}^{2}\ eq./kWh}) \tag{12}$$

where

EP_x
–*Eutrophication potential (per* $PO_{-4}^{2}eq.$*) of nutrient substance x*
M_{nx}
–*Total mass of nutrient substance x per unit electricity generated*

2.2.6. Ozone depletion potential

Ozone is a variant of oxygen, an ozone molecule having three atoms of oxygen. The ozone layer coats the earth's stratosphere, protecting the earth against the harmful ultraviolet rays of the sun by absorbing most of the hazardous UV-B radiation. Damage of this layer of ozone exposes the earth's surface to increased UV-B radiation. Emission of chlorofluorocarbons (CFCs) can cause thinning of ozone layers. The majority of ozone depleting substances were banned in the Montreal Protocol in 1989; however since this protocol does not prohibit non-signatory countries from using products that use CFCs in manufacturing, CFCs along with other halogenated hydrocarbons are still widely used in industrial non-signatory countries. The energy technology's ozone depletion potential is calculated as:

$$\textit{Ozone Layer Depletion Potential} = \sum_{x}^{X} OP_x \times M_{ox} \ (\mathrm{kgCFC_{-11}\ eq./kWh}) \tag{13}$$

where

OP_x
–*Ozone depletion potential (per* CFC_{-11} eq.) *of emission x*
M_{ox}
–*Total mass of ozone depletion substance per unit electrictiy generated*

2.3. Social sustainability indicators

The social impact of energy technology is measured in two categories; its ability to alleviate fuel poverty, and provision of employment.

2.3.1. Fuel poverty

An energy technology's ability to reduce fuel poverty is assessed using the reduction in energy bills achieved through the deployment of the chosen energy technology. It is calculated as (14):

$$\textit{Bill Reduction Rate} = \frac{E}{E_p} \times 100\ (\%) \tag{14}$$

where

E
–*Savings on electricity expenses through installation of energy technologies*
E_p
–*Electricity expenses prior to installation of energy technologies*

2.3.2. Employment provision

Renewable energy is often promoted for its associated effect on job creation. A major social contribution that an energy technology is expected to deliver is employment provision, and it is calculated as:

$$\textit{Employment provision} = \frac{\sum_{i=1}^{I} LE_i}{E_t} \tag{15}$$

where

LE_i – *Employment generated at life cycle stage i*

3. Product selection

Approximately 80–90% of solar cells produced today are made from single- (or mono-) and poly-crystalline [39]. Mono-crystalline silicon (also known as single-crystalline silicon, or s-Si) cells are made from silicon in the form of single crystal, and there are no boundaries between the silicon grains. This type of solar cell has high grade silicon material content and is known for its highest efficiencies (13–18%) among all the commercialised solar cell types, and thus it is more costly compared to other types of solar cells. Poly-crystalline silicon (p-Si) cells are of relatively lower silicon content that the silicon is made from an agglomeration of crystals distributed in various orientations, which means electron-hole-recombination losses are unavoidable due to the boundaries between silicon grains. The p-Si cells has a lower efficiency compare to s-Si cells, and it is less costly.

Another type of solar cells is thin film solar cells, it is a less popular option for its lower efficiency compared to the silicon based solar cells. They are made of exceedingly thin layers of photovoltaic materials spread on glass or stainless steel, and sometimes plastic backings. Because of the reduced use of semiconductor materials, the efficiencies are lower for thin film solar cells and thus this type of cell is less costly in comparison to the previous two types. Cadmium telluride (CdTe) solar cells are the most common thin film solar cell; it is also the most controversial type of PV technology for its use of cadmium, which is a toxic and hazardous material. Although under normal circumstances the toxic substance is not released into the environment, in cases of fire, breakage and inappropriate recycle handling, currently-available CdTe can escape from the solar cells and contaminate the environment.

Almost all installed solar PV systems in the UK are connected to the existing electricity grid. A proportion of the power generated is consumed on site by the host, with any surplus power generated being exported to the distribution network for regional distribution.

In the North East region, 95% of installed solar PV systems are residential, grid connected systems [40] at 4 kW (nominal maximum) capacity, and include the solar modules themselves, inverters and mounting parts (also known as Balance of the System, BoS). This study is focused on solar PV technologies that are already installed in the North East England. Therefore a 4kWp residential roof-mounted grid-connected system is considered for this study. Solar cells of two types of silicon material as well as CdTe solar cells are selected to be representative of the existing installation type. The functional unit of this study is per unit of electricity produced by the selected solar PV system.

Fig. 3. Lifecycle stages of solar PV.

4. System boundaries

The system boundary defines to what extend the product's life cycle is analysed. Based on existing literature (e.g. [11,15]), four life cycle stages of solar PV are included in this study: manufacture of the equipment, installation, operation and end of life (Fig. 3). The electrical grid connection is already in place prior to deployment of solar PV; therefore it is not included in the system boundary.

A solar PV system includes the solar panel, the inverter and the mounting parts. The manufacturer-guaranteed lifetime of a solar PV system is 25–30 years; after this period the energy system is still able to generate electricity at reduced efficiency, but to date there is no established data defining the drop-off time or efficiency reduction amounts. Therefore a range of 25–30 years is considered to be the lifetime of a solar PV system.

5. Assumptions

Environmental impact is widely computed using a process-based model, also known as SETAC approach, because of the high accuracy of this approach. GaBi is one of the most commonly used software applications for computing the SETAC approach among large companies and academia; it is therefore used to evaluate the environmental impacts of the solar PV systems in this study. The Ecoinvent3.0 [41] database is used to provide information on material and energy flows in the processes involved in the life cycle.

When assumptions are made, minimum and maximum values are provided where possible. For data quality assurance, the inclusion of assumptions in this study follows the ISO14044 guidelines [23]:

1. Data used are up to date.
2. Data are selected from relevant geographical locations to satisfy the goal of the study.

5.1. Key technical parameters

A list of key technical parameters is presented in Table 2. The efficiencies of the different types of solar PV modules are mentioned in the previous section. The cost of solar PV system varies depending on the manufacturer and equipment provider. A quotation provided by a local solar PV installer, Minel Energy, suggests that the cost of a 4kWp system alone varies from £3000 for the less popular CdTe cells to a maximum of £6000 for an s-Si system, with the installation cost ranging be-

Table 2
Key technical assumptions of solar PV systems.

Parameters	Types of material					
	Silicon				Thin film	
	s-Si		p-Si		CdTe	
	Min	Max	Min	Max	Min	Max
Life-time (years)	25	30	25	30	25	30
Module Efficiency	16%	18%	15%	16%	6%	10%
System Cost (£/system)	5000	6000	4000	4500	3000	3500
Installation cost (£/system)	800–1000					
O&M cost (£/system life time)	1200–1500					
Discount rate	3.5%					
Lifetime energy consumption (kWh)	53611				63055	
Annual Sunlight hours (hour)	1316–1230					
Annual energy yield per system (kWh)	4280	4800	4000	4280	1600	2680

tween £800 and £1000 for each system installed regardless of the panel material. Throughout their lifetime solar modules need to be cleaned to ensure optimum power output, and in some cases, the inverter needs to be replaced after 10 years. The majority of the solar installers offers a maintenance plan at the cost of £1200–£1500. A discount rate of 3.5% is applied according to the Green Book [42]. Lifetime energy consumption is estimated by Ecoinvent [41], including the end of life treatment for both recoverable and unrecoverable waste, and is in line with existing literature [43].

The average annual sunlight hours of the North East region is between 1316 and 1230 h [44]. Annual energy yield is estimated based on the module efficiency rate and solar irradiation and ranges from 1600 kWh generated by CdTe at an efficiency of 6%, to 4800 kWh generated by the maximum possible efficiency of s-Si. A general annual efficiency degradation rate of 1% is applied to all solar PV systems [45].

Income from a solar PV installation is generated through a Feed in Tariff (FiT) and the export of surplus electricity to the grid, in addition to bill reduction achieved by consuming the on-site generated electricity. The UK FiT currently offers a solar PV host 4.39 pence per kWh generation [46]. PV systems in the UK are mostly currently installed without export meters and exported electricity is set to a deemed amount of 50% for such systems. System hosts receive a rate of 4.85p/kWh for the deemed 50% of electricity exported, which is thus irrespective of the actual surplus export amount. Both FiT rate and export rate are discounted in the analysis by a Retail Price Index of 1.3%.

Table 5
Recoverable mass of silicon and CdTe solar PV systems.

Material (kg/system)		Types of solar panel	
		Silicon	CdTe
Recoverable mass	Aluminium	70.69	0.40
	Copper	3.54	8.36
	Board box	26.64	33.18
	Glass fibre reinforced plastic, polyamide	0.53	0.31
	Polyethylene terephthalate	6.27	0.00
	Silicon product	2.90	0.00
	Glass	383.48	538.20
	Steel	0.00	3.38
	Waste plastic	12.3032	5.1688

5.2. Environmental parameters

The UK is a relatively new market for PV; there have not been enough retired PV systems for the industry to establish a standard end of life treatment approach. So far, most of the UK's retired solar PV panels are processed as domestic waste, or occasionally transported to centralised European treatment facilities [47]. Therefore assumptions about end of life treatment are made presuming the assessed PV panels are recycled to the maximum amount at current technology: silicon panels are dismantled, and components are recycled separately at the current material recycling rate (as shown in Table 5). However, the case is different for CdTe systems because of the toxicity of the semiconductor material. Therefore the end of life solar panel scenario for CdTe system is assumed to follow the practice of the largest European-based manufacturer, First Solar's Frankfurt-Oder plant in Germany (as shown in Fig. 4). The retired CdTe panels are treated through shredding, removal of the semiconductor film, solid-liquid separation, laminate foil-glass separation and rinsing, semiconductor precipitation, and dewatering. Eventually, the module is reduced to glass cullet and unrefined semiconductor material and recycled at their current material recycling rate

Material composition for solar PV system varies slightly depending on the model and manufacturer. Therefore an estimate of the total material consumption per system according to a European dataset provided by Ecoinvent [41] is considered to be representative of the installed systems in the UK and is applied in this study. The total material consumption of solar PV systems is listed in Table 3. The dataset for s-Si and p-Si are identical in Ecoinvent 3.0. Hence a general estimation of the silicon-based system is used instead.

Recyclability is the percentage of material that can be reused after the product is recycled. In theory all metal, glass and silicon products have 100% recyclability; however in reality only a proportion of the material is sorted and recycled, the amount varying depending on the common recycling practice in the region. A list of the UK national specific material recycling rates of the recyclable materials is listed in Table 4.

Based on the above assumption, an estimation of recoverable mass for silicon and CdTe systems can be made and are listed in Table 5 below.

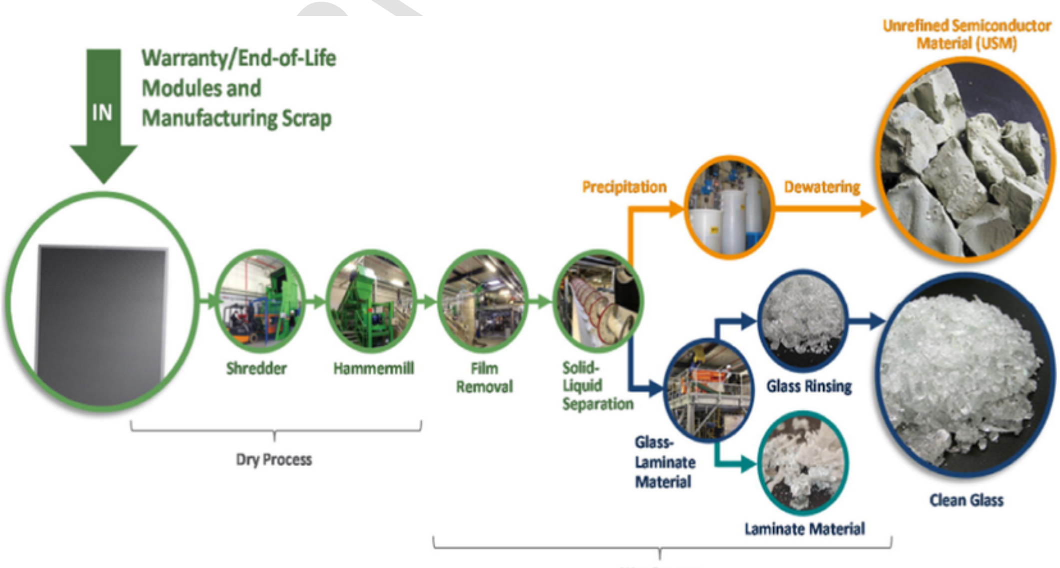


Fig. 4. End of life treatment of retired CdTe solar PV panels [48].

Table 3
Material consumption and waste for the treatment of solar PV system.

Material use (kg/system)		Types of solar panel material	
		Silicon	CdTe
Input material	Aluminium	73.64	0.42
	Copper	6.16	14.56
	Board box	30.80	38.36
	Ethyvinylacetate	28.00	16.80
	Glass fibre reinforced plastic, polyamide	5.32	3.08
	Polyethylene terephthalate	10.44	0.00
	Silicon product	3.42	0.00
	Silica sand	0.00	1.40
	Glass	565.60	793.80
	Steel	0.00	6.50
	Sodium chloride	0.00	1.40
	Sodium hydroxide	0.00	1.40
Waste for treatment	Municipal solid waste	0.84	27.28
	Waste plastic mixture	47.32	19.88
	Waste polyvinyl fluoride	3.08	0.00

Table 4
UK Specific material recyclable rate (It should be noted that plastic only be down cycled, it is therefore considered as recoverable waste).

Material	Recycle rate	Source
Aluminium	96.0%	[49]
Copper	57.4%	[50]
Board box	86.5%	[50]
Glass fibre reinforced plastic, polyamide	10.0%	[51]
Polyethylene terephthalate	60.0%	[52]
Silicon product	85.0%	[50]
Glass	67.8%	[50]
Steel	52.0%	[53]
Unrefined semiconductor material	95.0%	[48]
Plastic	26.0%	[54]

5.3. Social assumptions

The average UK domestic electricity bill is £578 per household in North East England based on an annual consumption of 3800 kWh in 2015 [55]. Solar PV is able to achieve employment provision of 653 person-year/TWh [38] regardless of the material used in the panel.

6. Results

This section presents the assessment results of solar PV systems. The techno-economic, environmental and social performances of the selected PV systems will be discussed separately, then a total ranking system will be applied to compare sustainability performances between the three selected types of PV systems. The complete set of results can be found in Appendix A.

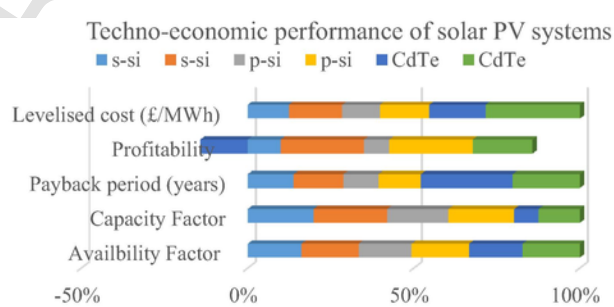
6.1. Techno-economic performance

The results for techno-economic performances are presented in Fig. 5.

The levelised cost of electricity generation varies from £74/MWh to £169/MWh. The availability factor entirely depends on the regional sunlight duration; it is thus at the same level for all PV systems. Conversely, the difference between silicon and CdTe for the rest of the indicators are rather noticeable. Despite the low system cost, the payback period and levelised cost of CdTe systems are almost double that of silicon-based systems. The profitability factor of CdTe in particular reaches negative values, which indicates high investment risk. It can be concluded that the economic performance of CdTe systems is constrained by their low efficiency; the levelised cost is compromised by its low lifetime electricity output, which thus further compromises both the payback period and profitability.

Other than cost and materials, climate and geographical location are the other factors that constrain the return on investment (ROI) for solar PV systems. For instance, a silicon-based solar panel installed in California has a capacity factor of 20%, which brings the levelised generation cost to as low as $7/MWh [56]; a horizontally-mounted silicon solar panel in Scandinavia has a capacity as low as 5.4% [15] which is almost as low as the lowest estimation for the worst performing CdTe systems in this study.

The two selected silicon PV systems are both able to pay back the capital costs between 10–14 years, which is approximately within the first half of their generating lifetime (normally 25 years). The p-Si system can achieve break-even as early as four years ahead of s-Si systems. Due to its lower generation capacity, the CdTe system will not break even until possibly after the generating lifetime has passed.



	Availbility Factor	Capacity Factor	Payback period (years)	Profitability	Levelised cost (£/MWh)
s-si	0.14	12%	13	0.84	74
s-si	0.15	14%	14	2.12	96
p-si	0.14	11%	10	0.65	68
p-si	0.15	12%	12	2.12	88
CdTe	0.14	5%	26	-1.2	101
CdTe	0.15	8%	19	1.53	169

Fig. 5. Techno-economic performance of solar PV systems.

In summary, solar PV systems made of silicon materials perform better as a result of a higher yield of electricity, and also lower investment risk, in comparison to CdTe systems. The p-Si systems require the least capital investment and have the best performance among the three selected solar PV systems in the techno-economic category.

6.2. Environmental performance

Environmental performance of silicon and CdTe systems are illustrated in Fig. 6. GaBi professional v6.115 and Ecoinvent 3.1 [41] integrated database are used for producing these results. This is because the dataset for s-Si and p-Si systems are identical in the Ecoinvent database, and a generalised silicon-based PV system is used as a representative of both s-Si and p-Si systems.

The minor difference on material circularity can be found between the two compared systems, with the silicon-based system valued slightly higher than the CdTe system on this indicator. The circularity of both assessed systems is compromised by the current material recycling rate in the UK. In theory, silicon-based solar PV has a recycling rate of as high as 99.7% [57]; however result from this study conveys that less than half of the material consumed and waste produced is neither recycled nor recyclable. For example, as previously shown in Table 3, the bulk of the mass for both PV systems is glass; in theory, the glass is 100% recyclable without loss in quality, [58] while compare to currently only 67.8% of the glass is recycled in the UK [50].

The energy payback period had exceed ten years for both the silicon and CdTe systems; the silicon-based system requires half of the manufacture guaranteed lifetime to reach energy break-even while the CdTe-based system will not achieve break-even within its guaranteed lifetime. Fig. 6 shows a breakdown of power consumption for the both systems. It can be observed that heavy energy demand for the end of life treatment of CdTe is the main reason for its poor energy payback performance, and this is directly linked to its use of CdTe materials. Although cadmium telluride is less toxic compared to cadmium alone, it still requires treatment in an energy-intensive industrial process to ensure it is separated from the solar panel and then treated separately to avoid contamination.

In comparison with CdTe systems, the manufacturing process for silicon-based systems consumes more energy (Fig. 7). The PV system manufacturing process is briefly illustrated in Fig. 8. The process for producing each solar cell begins with quartz reduction; then metallurgical grade silicon is purified by a Siemens or modified Siemens process which requires high temperatures in order for trichlorosilane and hydrogen to react in the reactor chamber; this is then followed by the silicon crystallisation process. In the case of s-Si panels, the Czochralski process which involves gradually extracting the growing crystal from the melting pot is required to produce silicon of single form (as previously explained in Section 3). These processes all requires a considerable amount of heat which therefore explains the high energy demand. In comparison, production of CdTe panels only involves applying a thin layer of semiconductor metal onto the glass backing, followed by a thermal treatment carried out with $CdCl_2$ [59].

The manufacturing process and end of life treatment of both solar PV systems also contribute to other environmental impact factors as can be observed from Figs. 9 and 10. The silicon purification process and the significant proportion of aluminium (76.64 kg) in the silicon-based system add to the system's high acidification and eutrophication potential. The ozone depletion potential originates from the silicon solar PV manufacture process and can be traced to panel wafer production where 30% are generated by German production and 60% are emitted from Asian and US factories, where environmental legislation for the manufacturing process varies greatly from that in Europe.

6.3. Social impacts

Existing data on employment creation through solar PV installation varies greatly [60,61]. This can be understood as the significant amount of job opportunities created through solar PV deployment are transferrable from other existing sectors such as construction and sales. In addition, there is a general lack of agreement on how job creation rate is recorded, which makes it difficult to form a complete picture on solar PV's ability to provide employment opportunities. Stamford [38] estimated a job creation rate of 653 person-year/TWh for the UK. As informed by Minel Energy, the difference in types of solar PV technology and geographical location has little impact on the number of employment opportunities created for installing and maintain solar PV.

The North East of England suffers from the highest proportion of households in fuel poverty across England, with 12% of the households falling into fuel poverty [62]. It can be observed from Fig. 11 that installation of a solar PV system can achieve a 36–54% bill reduction rate, which can assist in alleviating fuel poverty within the region.

6.4. Summary of solar PV technology comparison

The assessment results are organised using a total ranking system to identify the strengths and shortcomings of each assessed technology. Assuming all indicators are equally important,[1] a ranking score from 1 to 3 is assigned to each indicator based on the performance score of solar PV system at each category; where 1 represents the best performance and 3 accounts for the worst performance. The same ranking score is given to technologies that share the same performance within one category. All the scores are finally added to demonstrate the sustainability performance of each technology, where a lower score indicates better performance and a higher score worse performance.[2]

Examining the results listed in Fig. 6, thin film solar PV system has the worst performance across all categories, and s-Si system ranks higher in the social impact category owing to its higher energy conversion efficiency. Overall, the p-Si system is the most sustainable option.

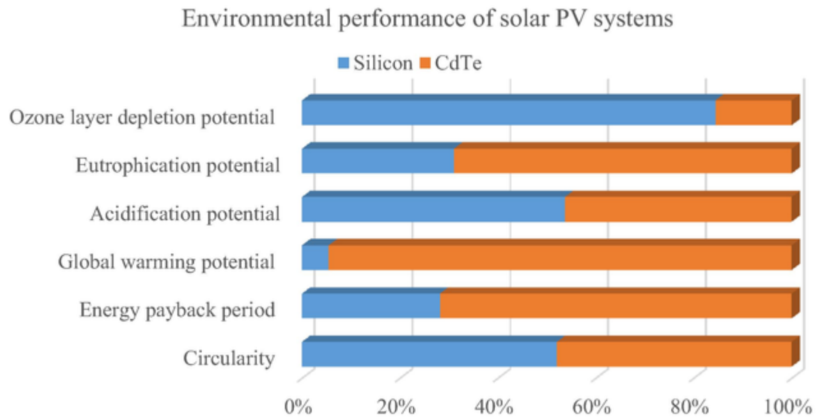
7. Discussion

7.1. Economic assumptions

In the assessment carried out in this study, a standard real discount rate of 3.5% is applied to all solar PV systems in accordance to Social Time Preference Rate (STPR) published in the Green Book [42]. In practice, investors or decision makers may select a different discount rate to reflect their perception of financial risks, and thus discount rate varies from one case to another [26]. Financial risks can be influenced by some factors such as maturity of the technology, the proportion of marginal cost, the lumpiness of investment, market incentives, and policy. For instance, as suggested by Oxera [63], when carrying out financial analysis, renewable energy technologies such as wind and solar PV should be given a discount rate of 6–9%, as these technologies possesses moderate financial risk for their low dependence on subsidies. Nevertheless, this discount rate was calculated in 2011, and so the most recent discount rate had been adjusted to 3.5% to reflect the recent reduction on FiT reduction and geopolitical changes [46,64].

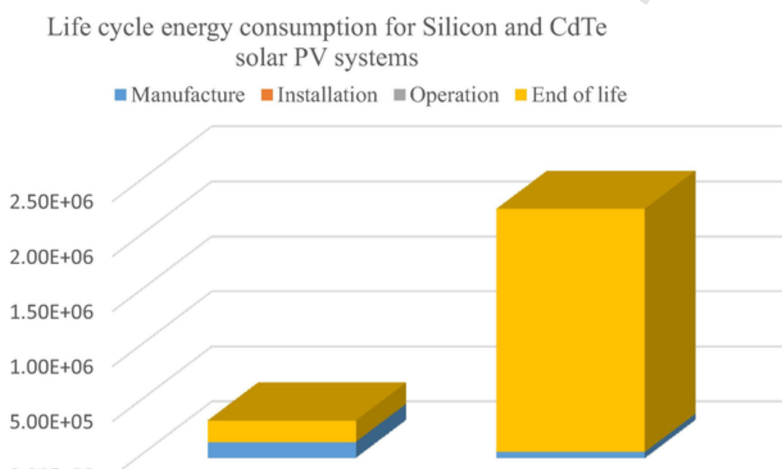
1 In accordance to sustainability theory, all three-pillars are considered to be equally important; therefore all indicators are considered to be equally important and no importance ranking score is applied.

2 The ranking does not take into account that the number of indicators is not evenly distributed among the three sustainability impact categories.



	Circularity	Energy payback period	Global warming potential	Acidification potential	Eutrophication potential	Ozone layer depletion potential
Silicon	0.38	12	1.19E+04	7.75E+01	2.88E+01	1.48E-03
CdTe	0.35	31	2.06E+05	6.68E+01	6.40E+01	2.73E-04

Fig. 6. Environmental performance of solar PV systems.



	Si PV system (MJ/system)	CdTe PV system (MJ/system)
End of life	1.93E+05	2.21E+06
Operation	1.07	3.80
Installation	0.61	0.79
Manufacture	1.46E+05	5.56E+04

Fig. 7. Lifecycle energy consumption of silicon and CdTe solar PV systems.

Finally, financial analysis carried out in this study does include the impact of administrative costs such as insurance cost and financing costs on the levelised cost of generation. These costs are influenced by the individual financing method and future technology learning, and these factors are not in the scope of this study. Nonetheless, these factors are recommended to be considered for future studies, particularly for the case of silicon-based solar PV modules, where the manufacturing cost of silicon wafers accounts for over 65% towards the total manufacturing cost of a solar cell and the majority of this cost occurs during the extraction and processing of silicon materials. In addition, with improvements in silicon recovery technology, the system cost is expected to reduce in the near future [65].

7.2. Policy support

Economic barriers are both complex and significant when it comes to the deployment of renewable energy technologies [66]. Successful renewable energy diffusion with help from policy support are evident in many countries such as Japan [67], Germany [68] and the US [69]. Strong policy support not only softens financial burdens but also encourages investor confidence which then subsequently advances R&D of the technology itself. Solar PV as an investment option requires a substantial proportion of capital investment which exceeds 60% of the total investment (Table 2). Additionally, the economic feasibility of solar PV heavily relies on available financial incentives where FiT tariff accounts for 25–60% of the total levelised cost (at 3.5% discount rate) [63,64].

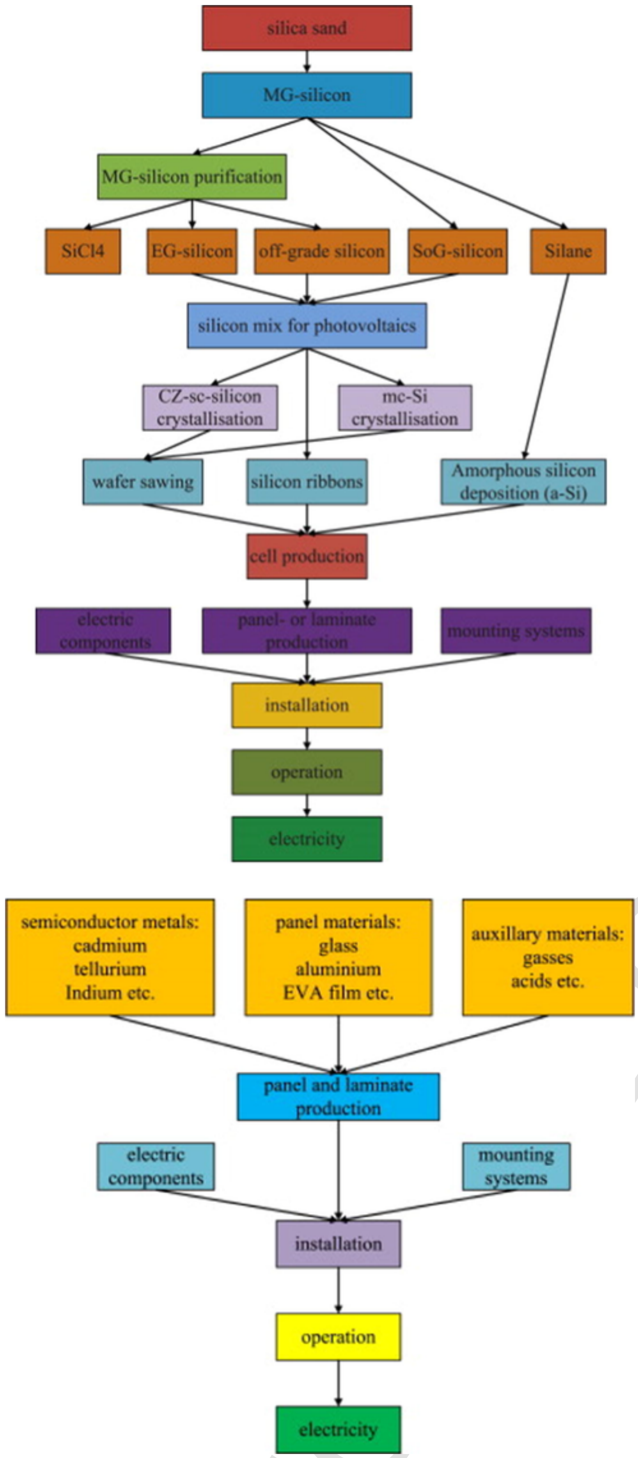


Fig. 8. Manufacture process of silicon-based (top) and thin film (down) solar PV systems [43].

7.3. Sensitivity analysis

In compliance with LCA standard ISO 14044 [23], additional analysis has been carried out for data quality assurance purpose. Other than the CML method used in this study, ReCiPe is another both geographically valid and widely applied LCA method with thoroughly peer-reviewed impact categories [29,70]. ReCiPe consists of both the mid-point and end-point method. For consistency purposes, only mid-point indicators that assess the same environmental impacts are included in this section. The results obtained from the ReCiPe method uses the same assumption, system boundary and process with that of the CML method.

Figs. 12 and 13 show the environmental impact assessment result (apart from circularity and energy payback period as they were not assessed using CML method) for silicon and CdTe solar PV systems carried out using ReCiPe method. In the ReCiPe method, eutrophication potential is divided into freshwater and marine eutrophication potential, and acidification potential is defined as terrestrial acidification potential.

The environmental impact for both solar PV systems is almost identical using LCA methods, apart from the eutrophication potential. The difference is more prominent for silicon systems, where the eutrophication potential using the CML method gives a total of $28.73\ \mathrm{kgPO}^{2}_{-4}$ eq./kWh, where the ReCiPe method gives a total of $10.84\ \mathrm{kgPO}^{2}_{-4}$ eq./kWh. This difference originates from different eutrophication potential calculation algorithms between the CML and ReCiPe methods. The CML method calculates eutrophication potential based on LCA background research carried out in 1992 [71], which assumes the worst case scenario by summing all nitrogen, potassium and organic matter emission in the phytoplankton molar element ratio of 106:16:1 for C:N:P, and no cause-effect mechanism is taken into consideration. On the other hand, the ReCiPe method is based on more recent research [72], and calculates eutrophication potential by categorising the receiving body where eutrophication substances are deposited which provides more precise modelling of environmental mechanisms with fewer substances covered [73]. Considering the above circumstances, it is considered that eutrophication potential results obtained using the ReCiPe method provide more credible estimation compared to the results obtained using CML method.

Furthermore, it should be noted that the end of life treatment technology for retired solar PV currently is still at development stage. Although recent technology enables a 60% recovery rate of silicon materials from retired PV panels [65], this technology has yet to be commercialised. Considering the material recovering rate of solar panels has the potential to reach as high as 96–99.7% [57], and the UK's WEEE directive is aiming to create a separate category for retired PV panels in the national legislation [47], the future for reduced environmental impact through improvement in both recycling practice and technology remains optimistic.

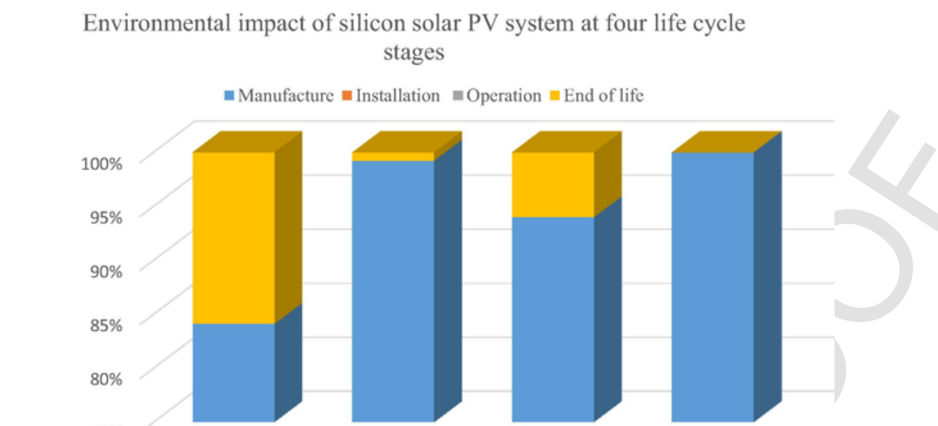
7.4. Sustainable supply chain

Solar PV is considered a "clean energy" by the general public, for the reason that it does not emit greenhouse gases during electricity generation. However, results from this study show that although solar PV technologies are emission-free during operation, the environmental impact derived from the manufacture and end of life treatment process are not negligible.

The economic globalisation and outsourcing of services has advanced the service of the supply chain, at the same time making it increasingly difficult for businesses and consumers to acknowledge and manage the impact of their decisions. Large companies have already started to demand more information from their suppliers and deploy LCA to track and optimise the sustainability performance of their products; and some companies have started to integrate LCSA in their sustainability strategy [22,74,75].

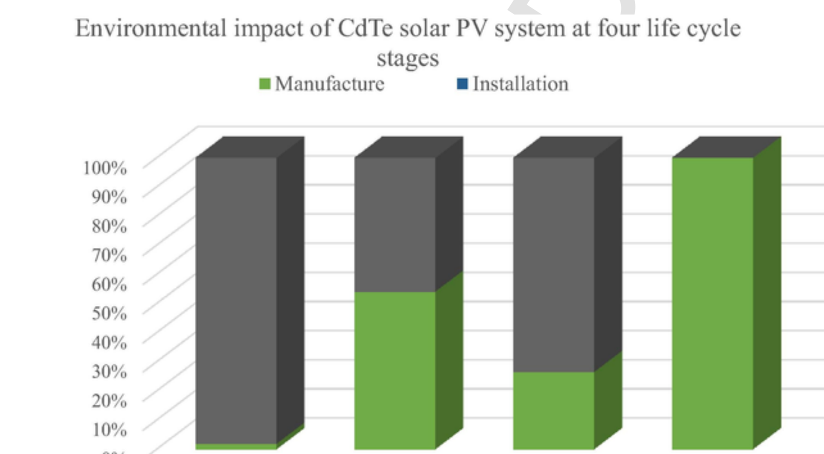
8. Conclusions

From the results of modelling and analysis above, it can be concluded that.



	Global warming potential	Acidification potential	Eutrophication potential	Ozone layer depletion potential
End of life	1.89E+03	6.00E-01	1.73E+00	0.00E+00
Operation	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Installation	3.88E-03	1.83E-05	4.36E-06	1.97E-10
Manufacture	1.00E+04	7.69E+01	2.70E+01	1.48E-03

Fig. 9. Environmental impacts of silicon solar PV system at four life cycle stages.



	Global warming potential	Acidification potential	Eutrophication potential	Ozone layer depletion potential
End of life	2.02E+05	3.07E+01	4.71E+01	3.24E-09
Operation	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Installation	6.76E-02	5.83E-04	7.66E-05	0.00E+00
Manufacture	3.84E+03	3.62E+01	1.70E+01	2.73E-04

Fig. 10. Environmental impacts of CdTe solar PV system at four life cycle stages.

The p-Si solar panel system is the most sustainable option among the solar PV systems made of p-Si, s-Si and CdTe materials. The sustainability performance of solar PV systems can be improved with future technology advancement.

In addition, solar PV technology is able to boost the micro-economy within a community by creating trade and employment opportunities, and it provides solutions for North East's fuel poverty issue. On the other hand, financing difficulties set up burdens for deployment of this technology.

The LCSA is a powerful and effective tool to evaluate and communicate sustainability information with stakeholders. The effectiveness of the designed model can be more pronounced when a mixed portfolio of technologies needs to be compared based on their sustainability performance. It should be noted that some factors may introduce bias to a study; for example, the sensitivity analysis carried out in this study revealed the bias associated with different LCA methodologies. Therefore it is recommended that possible bias-factors shall be carefully considered in future research, and the cross-validation method employed in this study has proven to be an effective tool.

For future application to cases involving different policymaking processes and market mechanisms, the assessment indicators can be modified to cater to the particulars of the application. The indicator selection process should follow the guidelines provided in this study, and the structure of the proposed model should remain unchanged.

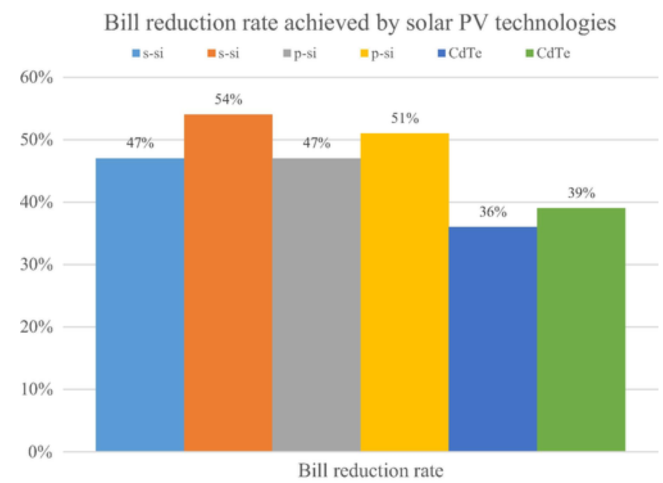


Fig. 11. Bill reduction rate achieved by s-Si, p-Si and CdTe solar PV systems.

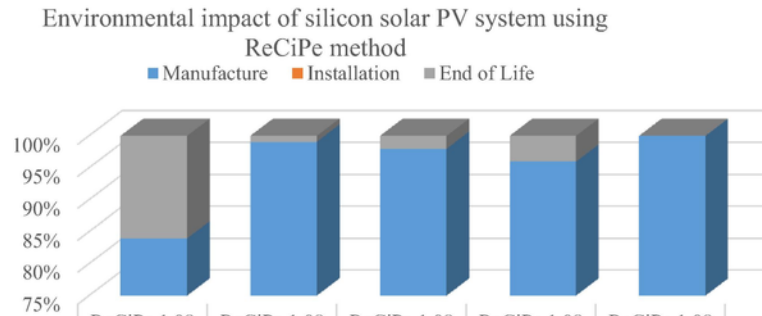
Appendix A

Sustainability assessment results for selected solar PV systems

Sustainability issues		Indicator			
					S
			s-Si		
			min	max	
Techno-economic category	Reliability	Availability factor			
		Capacity factor	12%	14%	
	Cost	Levelised cost	74	96	
	Financial feasibility	Payback period	13	14	
		Profitability	0.84	2.12	
Environmental category	Material circularity	Circularity			
	Energy Payback	Energy payback period			11
	Global warming	Global warming potential			1.
	Acidification	Acidification potential			
	Eutrophication	Eutrophication potential			
	Ozone depletion	Ozone layer depletion potential			1.
Social category	Fuel poverty	Bill reduction rate	47%	54%	
	Employment provision	Employment provision			

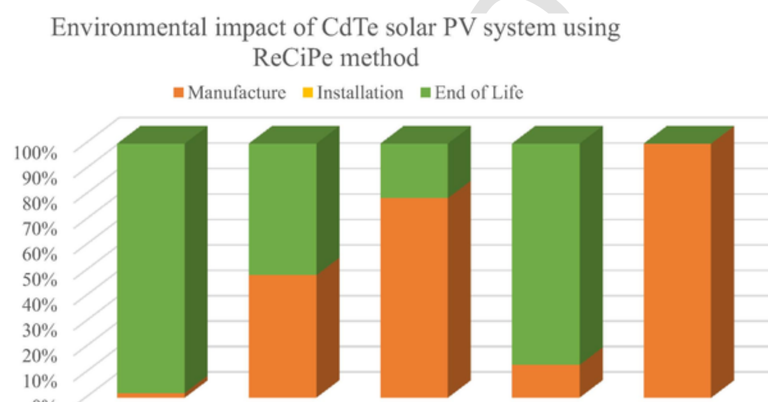
Table 6
Summarised sustainability ranking of solar PV systems.

Sustainability issues		Indicator	Type of solar photovoltaic systems		
			Silicon		Thin film
			s-Si	p-Si	CdTe
Techno-economic category	Reliability	Availability factor	1	1	1
		Capacity factor	2	1	3
	Cost	Levelised cost	2	1	3
	Financial feasibility	Payback period	2	1	3
		Profitability	1	2	3
	Sub-total		8	6	13
Environmental category	Material circularity	Circularity	1	1	2
	Energy Payback	Energy payback period	1	1	2
	Global warming	Global warming potential	1	1	2
	Acidification	Acidification potential	2	2	1
	Eutrophication	Eutrophication potential	1	1	2
	Ozone depletion	Ozone layer depletion potential	1	1	2
	Sub-total		7	7	11
Social category	Fuel poverty	Bill reduction rate	1	2	3
	Employment provision	Employment provision	1	1	1
	Sub-total		2	3	4
Grand total			17	16	28



	ReCiPe 1.08 Midpoint (H) - Climate change, default, excl biogenic carbon [kg CO2-Equiv.]	ReCiPe 1.08 Midpoint (H) - Terrestrial acidification [kg SO2 eq]	ReCiPe 1.08 Midpoint (H) - Freshwater eutrophication [kg P eq]	ReCiPe 1.08 Midpoint (H) - Marine eutrophication [kg N-Equiv.]	ReCiPe 1.08 Midpoint (H) - Ozone depletion [kg CFC-11 eq]
End of Life	1.90E+03	0.628	0.129	0.178	0
Installation	0.00386	1.57E-05	1.06E-06	5.02E-07	1.97E-10
Manufacture	9.95E+03	66.9	6.29	4.24	0.00151

Fig. 12. Environmental impact of silicon solar PV system using ReCiPe method.



	ReCiPe 1.08 Climate change [kg CO2-Equiv.]	ReCiPe 1.08 Terrestrial acidification [kg SO2 eq]	ReCiPe 1.08 Freshwater eutrophication [kg P eq]	ReCiPe 1.08 Marine eutrophication [kg N-Equiv.]	ReCiPe 1.08 Ozone depletion [kg CFC-11 eq]
End of Life	2.03E+05	3.39E+01	1.20E+00	1.25E+01	0.00E+00
Installation	6.69E-02	5.05E-04	1.48E-05	1.13E-05	3.25E-09
Manufacture	3.81E+03	3.15E+01	4.38E+00	1.85E+00	2.78E-04

Fig. 13. Environmental impact of CdTe solar PV system using ReCiPe method.

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